Detection of CO^+ toward the reflection nebula NGC 7023

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ABSTRACT

We have detected CO^+ toward the photon-dominated region (PDR) associated with the reflection nebula NGC 7023. This is the first detection of CO^+ in the vicinity of a Be star. A CO^+ column density of $\sim 3\ 10^{11}$ cm^{-2} has been derived toward the PDR peak. We have, however, not detected CO^+ in a well shielded clump of the adjacent molecular cloud, where the CO^+/HCO^+ abundance ratio is *at least 100 times lower* than in the PDR. Our results show, for the first time, that CO^+ column densities as large as $\sim 3\ 10^{11}$ cm^{-2} can be produced in regions with incident UV fields of just a few 10^3 (in units of Habing field) and densities of $\leq 10^5$ cm^{-3}. Furthermore, since the ionization potential of CO is larger than 13.6 eV, our data rule out the direct photoionization of CO as a significant CO^+ formation mechanism.

Subject headings: ISM: abundances — ISM: individual (NGC 7023) — reflection nebulae — stars: individual (HD 200775) — stars: pre-main-sequence — radio lines: ISM

1. Introduction

Although CO is the most abundant interstellar molecule after H_2, its corresponding ion, CO^+, is expected to have very low abundance in molecular clouds. The reason is that CO^+ is quickly converted into HCO^+ by reactions with H_2. Only in the hot layers of photon-dominated regions (PDRs) where a significant fraction of hydrogen is still in atomic form, the CO^+ abundance becomes significant. Chemical models (Sternberg and Dalgarno 1995) predict that for the PDRs associated with massive stars (n $\sim 10^6$ cm^{-3}, G$_\circ \sim 2\ 10^5$ in units of Habing field) the CO^+/HCO^+ abundance ratio is $\sim$0.05 at a visual extinction lower than 1.5 mag, but decreases by more than 2 orders of magnitude when the extinction increases above 3-5 mag. Based on its chemical behavior, they proposed the CO^+/HCO^+ ratio as a tracer of the HI/H_2 transition layer in PDRs.

CO^+ was tentatively detected for the first time by Erickson et al. 1981 toward OMC-1. Later, Latter, Walker and Maloney 1993 detected CO^+ in the well-known PDR M17SW and the planetary nebula NGC 7027. More recently, CO^+ has also been detected in the Orion Bar (Störzer, Stutzki and Sternberg 1995). But so far, all the detections of CO^+ have been made toward the interfaces between the molecular cloud and the HII regions around massive O stars. Störzer, Stutzki and Sternberg 1995 failed to detect CO^+ toward the reflection nebula S140. They propose that the large densities and intense UV fields associated with massive O stars are required to form CO^+ column densities $\geq 10^{11}$ cm^{-2}. We present the detection of CO^+ toward the reflection nebula NGC 7023, which is illuminated by a Be star. Although in this region the incident UV field is, $G_\circ \sim 10^3$ (in units of Habing field), and densities are, n $\sim 10^5$ cm^{-3}, we have observed a CO^+ column density of $\sim 3\ 10^{11}$ cm^{-2}. Furthermore, the spatial-velocity distribution of the CO^+ emission shows that CO^+ is only located within the HI/H_2 transition layer of this PDR.

2. Observations and Results

In Plate L1, we show the integrated intensity map of the HCO^+ 1→0 (thin dark contours) and the HI column density map (grey scale) of the reflection nebula NGC 7023 (Fuente et al. 1993 and Fuente et al. 1996). The illuminating star, HD 200775, is located in a cavity of the parent cloud delimited by dense walls (Fuente et al. 1993 and references therein). Dense PDRs are found on the surfaces of these walls. In particular, an intense HI clump appears ≈ 40 NW from the star position, at the edge of the bulk of the molecular emission (see Plate L1). Interferometric observations of the J= 1→0 line of HCO^+ showed the existence of several high density HCO^+ filaments within this clump (Fuente et al. 1996). The two most intense filaments are also shown in Plate L1. We have searched for CO^+ toward the peak position of these filaments. The coordinates of this position are given in Table 1 and hereafter, we will refer to it as the "PDR peak". Beyond the "PDR peak", our HCO^+ single-dish data show the existence of several clumps immersed in the molecular cloud. We have also searched for CO^+ toward the molecular clump closest to the "PDR peak" (Plate L1). The coordinates of this position are also given in Table 1 and hereafter, we will refer to it as the "Molecular Peak".

CO^+ has a $^2\Sigma$ ground electronic state in which each rotational level is split in two fine structure levels with J=N±1/2. The N=1→0 rotational line is heavily obscured by the O_2 line at 118 GHz and cannot be observed from ground-based telescopes. The most intense transitions of the N=2→1 rotational spectrum are N=2→1 J=5/2→3/2 at 236062.553 MHz and N=2→1 J=3/2→1/2 at 235789.641 MHz. In the optically thin limit, the intensity ratio I(235.789)/I(236.062) is 0.55 (Sastry et al. 1981). Both line frequencies were covered by the receiver band. Unfortunate, the most intense line is blended with the $5_{-2}\rightarrow 4_{-2}$ and $5_2\rightarrow 4_2$ $^{13}CH_3OH$ E lines (see Blake et al. 1984). In order to determine an upper limit to the $^{13}CH_3OH$ emission we have observed the $5_1\rightarrow 4_1$ methanol line toward the PDR peak. To

determine accurate CO^+ column densities, it is necessary to have accurate estimates of the hydrogen density. For this aim, maps of about 20"×20" with a spacing of 5" were carried out around the studied positions in the CS J=2→1, 3→2 and 5→4 lines. Furthermore, the $H^{13}CO^+$ J=1→0 (toward both positions) and 3→2 (only toward the molecular peak) have also been observed.

The observations were carried out in 1995 December and 1996 May using the 30-m telescope. The observational procedure was position switching with a fixed reference 30' East from the star. Pointing was checked every two hours using strong continuum sources (NGC 7027, K3-50A, NGC 7538), and the rms of pointing errors was less than 2". The forward and main beam efficiencies were 0.92 and 0.75 at 90 GHz, 0.90 and 0.52 at 145 GHz, and 0.86 and 0.37 at 236-260 GHz respectively. The temperature scale is main beam temperature. The HPBW of the telescope was 27" at 90 GHz, 16" at 145 GHz and 10" at 236 GHz. Typical system temperatures (in T_{MB}) were 300 K at 90 GHz, 600 K at 145 GHz, 1300K at 236 GHz and 3400 at 260 GHz. All the lines have been observed with a frequency resolution of 80 kHz ($\sim$ 0.1 km s^{-1} at 236 GHz).

EDITOR: PLACE TABLE 1 HERE.

2.1. PDR peak

The CO^+ N=2→1 5/2→3/2 and 3/2→1/2 lines have been detected toward the PDR peak with a signal to noise ratio of 10 and 7 respectively (see Plate L1). The observational parameters are shown in Table 1. The detection of both lines make very unlikely a possible misidentification. We are not aware of possible line contamination for the transition at 235789.64 MHz. The only possible line contamination comes from the $5_{-2}\rightarrow4_{-2}$ and $5_2\rightarrow4_2$ $^{13}CH_3OH$ E lines whose rest frequency is less than 0.5 MHz from the CO^+ line at 236062.55

MHz (see Blake et al. 1984). Since the observed linewidths of the two lines of CO^+ are the same, it seems that the line at 236062.55 MHz is very unlikely contaminated by $^{13}CH_3OH$ lines. To check for possible contamination, we have estimated an upper limit to the emission of the $^{13}CH_3OH$ lines from the observed $J_K=5_1 \rightarrow 4_1$ methanol line. The excitation conditions and the line strength for this line are very similar to those of the contaminating $^{13}CH_3OH$ lines (Anderson, De Lucia and Herbst 1990). Assuming a linewidth of 2 kms^{-1}, we have obtained a 3σ upper limit of 0.2 K kms^{-1} to the integrated intensity emission of the methanol line (see Table 1). For an isotopic ratio, $CH_3OH/^{13}CH_3OH \sim 40$, this would imply an upper limit of 0.005 K kms^{-1} to the integrated intensity emission of each $^{13}CH_3OH$ line. Since there are two $^{13}CH_3OH$ lines blended, these lines could contribute to our CO^+ detection at 236.062 GHz with, at most, an integrated intensity of 0.01 K km s^{-1}. This is only 4% of the observed integrated intensity emission at 236.062 GHz, and it is within the observational errors (see Table 1). We, therefore, conclude that the emission detected at 236.062 and 235.789 GHz is due to CO^+.

A striking result of our data is that the CO^+ lines have linewidths much larger than those of CS and $H^{13}CO^+$. The interferometric HCO^+ filaments detected toward the PDR peak are characterized by having different velocities. The four well detected filaments are centered at radial velocities of 1.9, 2.4, 2.8 and 4 km s^{-1}, and the one tentatively detected is centered at 5.8 kms^{-1}. One of these filaments, 2.4 kms^{-1}, is very likely embedded in the molecular cloud, but most of the others, 2.8, 4.0 and 5.8 km s^{-1}, seem to be immersed in the atomic medium. The situation is less clear for the filament at 1.9 kms^{-1} that seems to be part of a weak and extended molecular component (Fuente et al. 1996). Therefore, a gradient in the chemical composition of the HCO^+ filaments is expected depending upon the local visual extinction toward the exciting star. CS and $H^{13}CO^+$ present narrow lines centered at 2.4 kms^{-1}, i.e., the velocity of the filament immersed in the bulk of the molecular cloud. Only HCO^+ and CO^+ present emission at the velocities of the filaments

immersed in the atomic medium. From the comparison of the spectra of the $H^{13}CO^+$, HCO^+ and CO^+ lines, it is clear that there exists a gradient in the CO^+/HCO^+ abundance ratio as a function of velocity, i.e., as a function of the visual extinction from the star (see Plate L1). To determine this gradient, we have estimated the CO^+/HCO^+ abundance ratio in three different velocity intervals, 0 - 1.6 km s^{-1}, 1.6 - 3.2 km s^{-1}, and 3.2 - 6 km s^{-1}.

CO^+ column densities have been estimated using the LTE approximation. Assuming T_K = 40 K (see Fuente et al. 1993) we derived from CS data a hydrogen density of ∼3.5 10^5 cm^{-3} for the component at 2.4 km s^{-1}. Similar densities were obtained for the other filaments from the interferometric HCO^+ data (Fuente et al. 1996). Using a LVG code and assuming T_k = 40 K and n = 3.5 10^5 cm^{-3}, we estimate T_{rot} = 10 K for HCO^+. Since HCO^+ and CO^+ have similar dipole moments and rotational constants (μ = 2.77 D for CO^+ and 3.91 D for HCO^+), we assume the same rotational temperature for CO^+. In Table 2 we show the derived HCO^+, $H^{13}CO^+$ and CO^+ column densities. From these estimates, we have determined that the CO^+/HCO^+ abundance ratio is a factor of 10 larger for the filaments immersed in the atomic region than for the filaments embedded in the molecular cloud. This gradient in the CO^+/HCO^+ ratio cannot be due to an opacity effect. The I(CO^+ 235.789)/I(CO^+ 236.062) ratio is consistent with optically thin emission (within the observational errors) for all the velocity intervals (see Table 2). Though consistent with optically thin emission, our data suggest that the opacities of the CO^+ lines could be larger for the velocities 3.2 - 6.0 km s^{-1} than for 1.6 - 3.2 km s^{-1}. In this case, the CO^+ column density would be slightly underestimated for the velocity interval 3.2 - 6.0 km s^{-1}, and the derived CO^+/HCO^+ ratio would be a lower limit to the actual value of the CO^+/HCO^+ ratio for this interval. Therefore, although we are aware of the uncertainties involved in column density estimates, we think that the observed gradient in the CO^+/HCO^+ ratio (a factor of 10) is significant, and it is in agreement with the expected behavior of the CO^+/HCO^+ ratio, where CO^+ formation is restricted to a narrow range of visual

extinctions $A_v < 2$ mag. The visual extinction at the surface of the filament at 2.4 km s^{-1} must be >1 mag to be immersed in a mainly molecular medium, while for the filaments immersed in a mainly atomic medium, the visual extinction must be <1 mag. Assuming a HCO^+ fractional abundance of 4 10^{-10} (Fuente et al. 1996), the CO^+ fractional abundance is $\sim$ 4 10^{-11} in the filaments immersed in the atomic medium. CO^+ fractional abundances $\sim 10^{-11}$ are also derived from the CO^+ data reported by Störzer, Stutzki and Sternberg 1995 and Latter, Walker and Maloney 1993, toward M17SW and the Orion Optical Bar. Although the physical conditions and incident UV field are different (see Section 3), the CO^+ fractional abundance in NGC 7023 is similar to that found at the edges of the HII regions around massive stars.

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2.2. Molecular peak

We have not detected CO^+ toward the molecular peak. Assuming a linewidth of 1 km s^{-1} (a typical linewidth for the molecular cloud), we obtain an upper limit to the integrated intensity of the CO^+ line at 236.062 GHz of 0.03 K kms^{-1}. Assuming a kinetic temperature of T_K = 15 K (Fuente et al. 1990), we estimate a density of 10^5 cm^{-3} from our CS data. This density is high enough to excite the CO^+ lines. In fact, the excitation conditions required for the $H^{13}CO^+$ J=3$\rightarrow$2 line are comparable to those required for the CO^+ N=2$\rightarrow$1 J=5/2$\rightarrow$3/2 and 3/2$\rightarrow$1/2 lines, and the $H^{13}CO^+$ J=3$\rightarrow$2 line has been detected with an intensity of 1.04 K. Therefore, the lack of detection of CO^+ toward the molecular peak is not due to the excitation conditions in this region. With the same assumptions as for the PDR peak, the upper limit to the CO^+ column density is 4.5 10^{10} cm^{-2}. Assuming n = 10^5 cm^{-3} and T_K = 15 K, we estimate a $H^{13}CO^+$ column density of 8 10^{11} cm^{-2}. This means a

CO^+/HCO^+ ratio of < 0.001. Therefore, the $CO^+/H^{13}CO^+$ ratio is *at least 100 times lower* in the molecular peak than in the filaments immersed in the atomic medium. Assuming a HCO^+ abundance of 4 10^{-10}, we obtain a fractional abundance of CO^+ of <5 10^{-13} in the molecular peak.

3. Summary and Discussion

We have detected, for the first time, CO^+ in a PDR associated with a Be star. This region is very different from the massive star forming regions where CO^+ had been detected thus far. First of all, since the ionization potential of CO is larger than 13.6 eV, a Be star does not produce a significant number of photons capable to ionize CO. Furthermore, the intensity of the UV field and the density around this star, $G_\circ \sim 10^3$ (in units of Habing field), and densities of $\sim 10^5$ cm^{-3}, are very different from those around massive O stars where $G_\circ \sim 10^5$ and $n \geq 10^6$ cm^{-3}. Chemical models predict that CO^+ column densities decrease sharply for UV fields $<10^5$, and densities $<10^6$ cm^{-3} (Störzer, Stutzki and Sternberg 1995). Even for the conditions prevailing in massive star forming regions, chemical models fail to predict the large CO^+ column densities observed toward them. To solve this problem, some authors have suggested that the direct photoionization of CO might be a non-negligible formation mechanism of CO^+ in these regions (Jansen et al. 1995, Black, Latter and Maloney 1996). We have estimated a CO^+ column density of ~ 3 10^{11} cm^{-2} toward the PDR peak in NGC 7023. Our results show that large CO^+ column densities can be produced even with UV fields of just a few 10^3 and densities of around 10^5 cm^{-3}. Since the peak CO^+ abundance in NGC 7023 ($\sim$ 4 10^{-11}) is similar to that found in massive star forming regions, our data suggest that the direct photoionization of CO is not a significant formation mechanism for CO^+.

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Fig. 1.— Left panel shows the integrated intensity map of the HCO^+ J=1→0 line carried out with the 30-m telescope toward NGC 7023 (solid contours) superposed to the HI column density image obtaining after combining VLA and DRAO data (grey scale) (Fuente et al. 1993, Fuente et al. 1996). HCO^+ contours are 0.8 to 7.2 by 0.8 K kms^{-1}. The numbers in the wedge are in units of 10^{20} cm^{-2}. The star indicates the position of HD 200775, the white triangle indicates the PDR peak and the filled black square, the molecular peak. The HCO^+ molecular filaments as observed with the IRAM PdB interferometer are the thick contours, black is the filament at 2.4 kms^{-1} and white the one at 4 kms^{-1} (Fuente et al. 1996). On the right we show (from top to down) the spectra of the HCO^+ J=1→0, $H^{13}CO^+$ J=1→0 CO^+ N=2→1 J=5/2→3/2 and J=3/2→1/2 lines toward the molecular peak and the PDR peak. Several channels of the original CO^+ spectra have been averaged.

Table 1: Observational parameters

Position	Molecule	Frequency (MHz)	$\int T_{MB} dv$ (K km s^{-1})	v$_{lsr}$ (km s^{-1})	Δv (km s^{-1})	T$_{MB}$ (K)
PDR peak	CO^+	235789.64	0.17(0.03)	3.4(0.2)	2.1(0.4)	0.076
R.A.:21^h 01^m 32^s.6	CO^+	236062.55	0.23(0.02)	2.7(0.1)	2.1(0.4)	0.104
Dec: 68° 10' 27"	CH_3OH	239746.25	<0.2[a]			
(2000)	CS	97980.97	0.92(0.04)	2.3(0.1)	0.7(0.1)	1.31
	CS[b]	146969.05	1.38(0.02)	2.3(0.1)	0.7(0.1)	1.85
	CS[c]	244935.61	0.79(0.03)	2.3(0.1)	0.5(0.1)	2.73
	$H^{13}CO^+$	86754.33	0.34(0.04)	2.38(0.04)	0.5(0.1)	0.61
Mol. peak	CO^+	235789.64	<0.03[d]			
R.A.:21^h 01^m 31^s.6	CO^+	236062.55	<0.03[d]			
Dec: 68° 11' 12"	CS	97980.97	1.02(0.02)	2.6(0.1)	0.7(0.1)	1.36
(2000)	CS[b]	146969.05	0.64(0.02)	2.7(0.1)	0.7(0.1)	0.9
	CS	244935.61	<0.04[d]			
	$H^{13}CO^+$	86754.33	1.10(0.01)	2.8(0.1)	0.7(0.1)	1.46
	$H^{13}CO^+$	260255.48	0.44(0.01)	3.0(0.1)	0.4(0.1)	1.04

[a] 3σ upper limit assuming a linewidth of 2 kms^{-1}

[b] Spectrum after degrading the angular resolution of the CS 3→2 map to have that of the CS 2→1 map.

[c] The same as b but for the CS 5→4 map

[d] 3 σ upper limit assuming a linewidth of 1 kms^{-1}

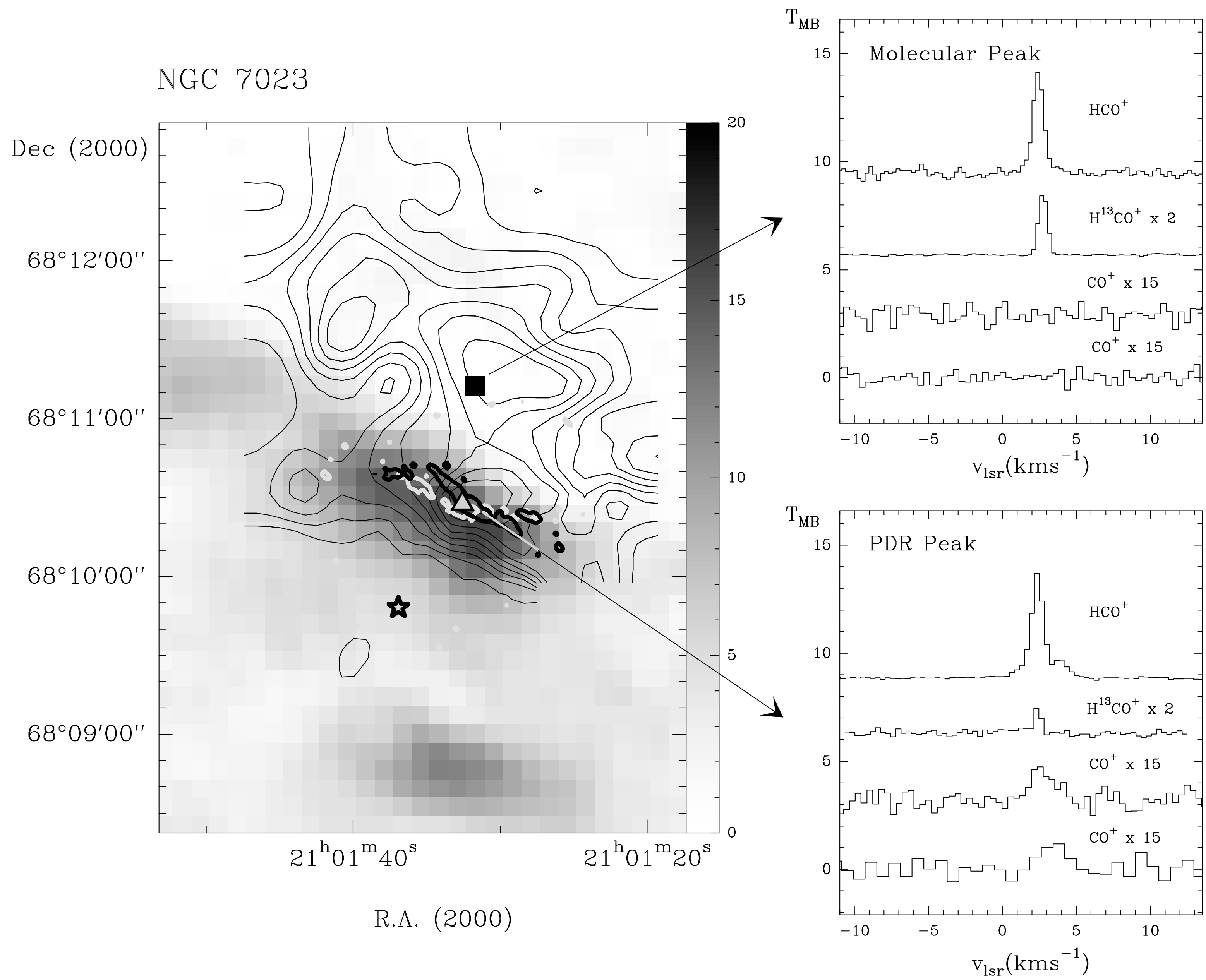
Table 2: Integrated intensities, column densitites and abundance estimates toward the PDR peak per velocity interval

	0 - 1.6 kms^{-1}	1.6 - 3.2 kms^{-1}	3.2 - 6.0 kms^{-1}
I(HCO^+ J=1→0) (K kms^{-1})	0.59(0.02)[a]	4.67(0.02)	1.10(0.03)
I($H^{13}CO^+$ J=1→0) (K kms^{-1})	0.11(0.04)	0.34(0.04)	<0.15
I(CO^+ N=2→1 J=5/2→3/2) (K kms^{-1})	0.02(0.01)	0.14(0.01)	0.07(0.02)
I(CO^+ N=2→1 J=3/2→1/2) (K kms^{-1})	<0.06	0.08(0.02)	0.09(0.03)
$\frac{I(CO^+ N=2\rightarrow1 J=3/2\rightarrow1/2)}{I(CO^+ N=2\rightarrow1 J=5/2\rightarrow3/2)}$		0.6(0.2)	1.3(0.8)
N(HCO^+) (cm^{-2})	5 10^{11}	4 10^{12}	9 10^{11}
N($H^{13}CO^+$) (cm^{-2})	8 10^{10}	3 10^{11}	
N(CO^+) (cm^{-2})	3 10^{10}	2 10^{11}	1 10^{11}
$\frac{N(CO^+)}{N(HCO^+)}$	0.01[b]	0.02[b]	0.11
X(CO^+)[c]	4 10^{-12}	8 10^{-12}	4 10^{-11}

[a] The number in parenthesis is σ

[b] In these cases, the HCO^+ column density has been estimated from $H^{13}CO^+$ data assuming an isotopic ratio of 40

[c] Assuming X(HCO^+) $\sim$ 4 10^{-10}


NGC 7023
Dec (2000)
68°12'00''
68°11'00''
68°10'00''
68°09'00''
21h01m40s
21h01m20s
R.A. (2000)
20
15
10
5
0
T_MB
Molecular Peak
HCO+
H13CO+ x 2
CO+ x 15
CO+ x 15
v_lsr(kms-1)
PDR Peak
HCO+
H13CO+ x 2
CO+ x 15
CO+ x 15
v_lsr(kms-1)